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Measuring Neutrino Cross-Sections and Neutrino Detector R&D at the Fermilab Antiproton Debuncher

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Abstract

The Fermilab Antiproton Debuncher, utilized as a poor-mans Neutrino Factory, would provide us with a unique resource for (i) measuring $\bar{\nu}_e$ cross-sections, (ii) investigating the performance of candidate detector technologies that might be proposed for the next big step in the neutrino oscillation physics program, and (iii) studying the backgrounds that are important for long baseline ν_e appearance searches. This note discusses neutrino fluxes, event rates, and the associated statistical precision that could be obtained with a 0.1 kt detector running parasitically during collider operation for 4 years, and located 15 m downstream of a Debuncher straight section.

1 Introduction

The Fermilab Antiproton Debuncher can be considered a poor-mans neutrino factory [1]. In this note we consider using the Debuncher to (i) measure $\bar{\nu}_e$ cross-sections, (ii) investigate the performance of candidate detector technologies that might be proposed for the next big step in the neutrino oscillation physics program, and (iii) study the backgrounds that are important for long baseline ν_e appearance searches.

The Debuncher is an 8.9 GeV/c storage ring with three long straight sections, each straight section accounting for 13% of the 500 m ring circumference. The momentum acceptance of the Debuncher is $\pm 2\%$. In normal operation the Debuncher collects negative particles, including negative pions which decay into muons within a few revolutions ($\gamma\tau_\pi \sim 1$ turn). Many of the muons are captured in the ring, and subsequently decay. The pion and muon decays generate neutrino beams downstream of each straight section which consist of a short burst of muon antineutrinos from π^- decay, followed by a longer burst of muon neutrinos and electron antineutrinos from μ^- decay. The intensity of these neutrino beams is insufficient for neutrino oscillation experiments [2]. However, the intensity is sufficient to consider an experiment designed to measure low energy neutrino cross-sections, and to study the response of prototype detectors for neutrino superbeams [3] and neutrino factories [4].

A first experiment at a Debuncher facility might consist of a 0.1 kt liquid argon (ICARUS-type [5]) detector located 15 m from the end of one straight section. The detector might be within a solenoidal field to enable muon charge-sign determination, and/or have an external muon spectrometer. Precise measurements of the low energy electron antineutrino cross-section, and the muon neutrino and antineutrino cross-sections could be made [6]. Knowledge of the quasi-elastic (QE) cross-sections, for example, is of importance for the analysis of low energy neutrino oscillation data. The existing QE measurements were made ~ 20 years ago [7, 8] and have very limited precision (Fig. 1). In addition to the QE cross-sections, backgrounds to ν_e appearance signals from π^0 production in neutral current (NC) events could be studied. If the liquid argon detector was within a solenoid, its ability to measure the charge of low energy electrons could be tested [6]. Finally, other detector types could be considered for the first experiment, or considered for subsequent testing at the facility.

In the following we will consider neutrino fluxes and event rates, the statistical precision of QE scattering measurements, and the effect of muon polarization in the ring.

2 Fluxes and Event Rates

The ratio of muons/antiprotons in the Debuncher has been measured [9] to be 1.0 ± 0.2. In the near future the antiproton accumulation rate is expected to reach about 30-50 mA/hour. This corresponds to $3-5\times10^{11}$ antiprotons per hour delivered by the Debuncher. In the following we will assume there are 4×10^{11} muons per hour decaying within the Debuncher. With 10^7 seconds per operational year, this yields 1×10^{15} muons per operational year, of which 13% will decay in a given straight section.

Let us assume that the experiment takes data parasitic to collider operations, and has to be completed by the end of 2007. If the experiment starts data taking in 2-3 years

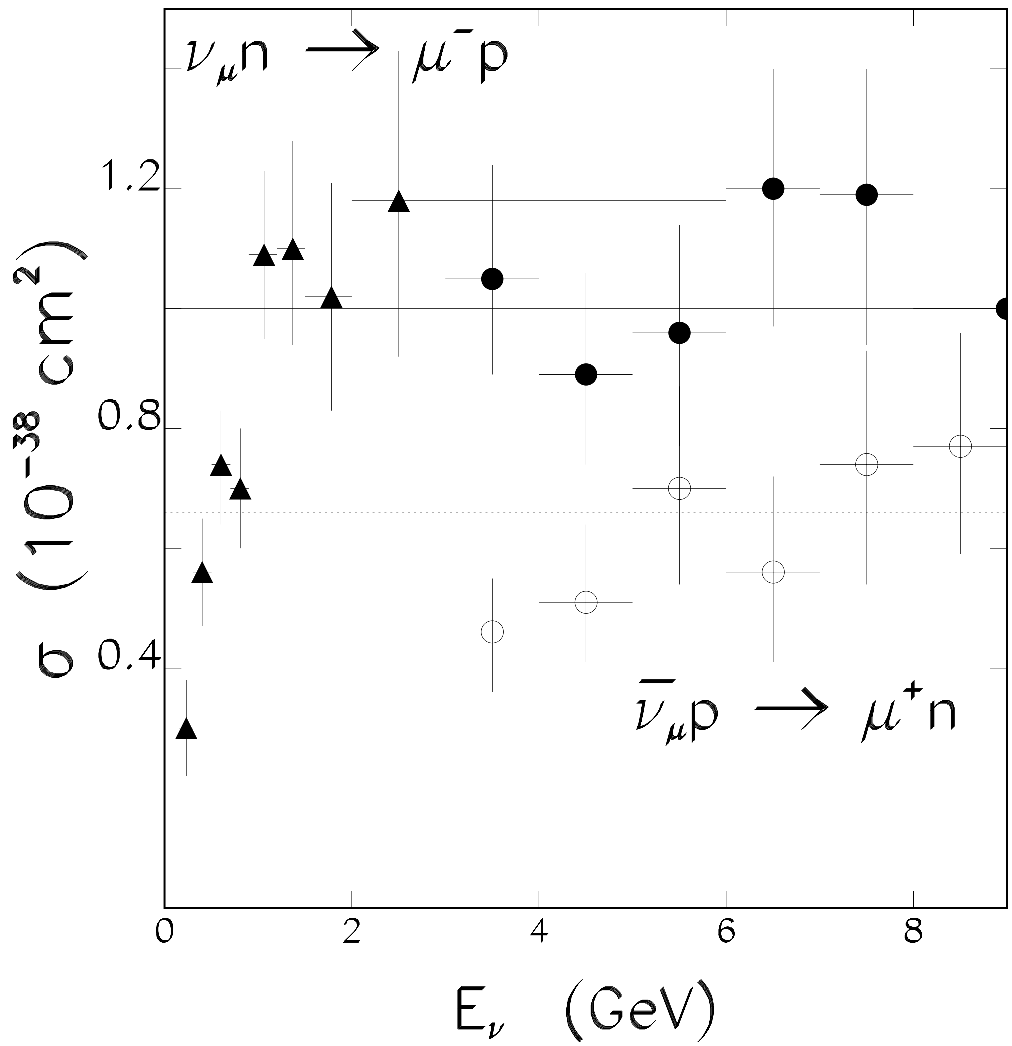

Figure 1: Measured cross-sections for quasi-elastic neutrino (solid points) and antineutrino (open points) scattering as a function of neutrino energy. The data are from [7] (triangles) and [8] (circles). The solid (broken) horizontal lines show the asymptotic high-energy neutrino (antineutrino) QE scattering rates obtained from V-A fits to the data.

Table 1: Estimated event rates for a 4 year run with a 0.1 kt detector 15 m downstream of a Debuncher straight section. The numbers are scaled from the estimates given in the P-860 proposal.

Process	Events / 0.4 kt-years
$\bar{\nu}_e$(all)	6330
$\bar{\nu}_e$(QE, SP only)	1440
ν_μ(all)	14500
ν_μ(QE,SP,DEEP)	4370
$\bar{\nu}_\mu$(π decay)(all)	181000
$\bar{\nu}_\mu$(QE,SP)	54600

from now, there would be 4 years of data, corresponding to 6×10^{14} muon decays in a given straight section. The typical neutrino opening angles are $O(1/\gamma \sim 0.1/8.9 = 0.01)$ radians. Hence, if the detector is located 15 m downstream of a 65 m straight section, the beam spot would be contained within a fiducial area with a radius of about 1 m. We can therefore expect the total flux of electron antineutrinos passing through the detector to be $\sim 6 \times 10^{14}$, accompanied by the same number of muon neutrinos. There will also be a much larger flux of muon antineutrinos from pion decay.

A first estimate of various event rates can be obtained by scaling numbers from the P-860 proposal [2] which described a potential neutrino oscillation experiment at the Debuncher. The P-860 rates were calculated for a detector with a fiducial mass of 0.7 kt, and special reversed polarity Debuncher running (positive particles collected instead of negative particles) with an assumed accumulation rate of 2.25×10^{12} per hour. Therefore, for our scenario we must scale the P-860 rates by $(4 \times 10^{11}/2.25 \times 10^{12}) \times (0.1/0.7) = 0.025$. In addition, since we want rates for normal running and not for reversed polarity operation, factors of 2 (0.5) must also be applied to the P-860 neutrino (antineutrino) rates to provide a rough correction for the difference between neutrino and antineutrino cross-sections (a better estimate of the QE event rates is given in the next section). The resulting estimated rates for 4 years of data taken parasitic to normal Antiproton Collider operations are summarized in Table 1. Note that these rates include a detector efficiency factor of 0.75, which allows for losses during the first 10 turns when the neutrino flux is dominated by muon antineutrinos from pion decays.

3 Quasi-Elastic Scattering Measurements

To estimate the QE event rates, and the precision with which the differential cross-section $d\sigma/dE_{\bar{\nu}_e}$ could be determined, we will use an approximate expression based on Fig. 1:

$$d\sigma(\nu_\mu n \to \mu^- p)/dE_\nu \;=\; (E_\nu/0.7) \;\times 10^{-38}\ \mathrm{cm}^2 \;\; \text{for} \;\; \mathrm{E}_\nu < 0.7\ \mathrm{GeV} \tag{1}$$

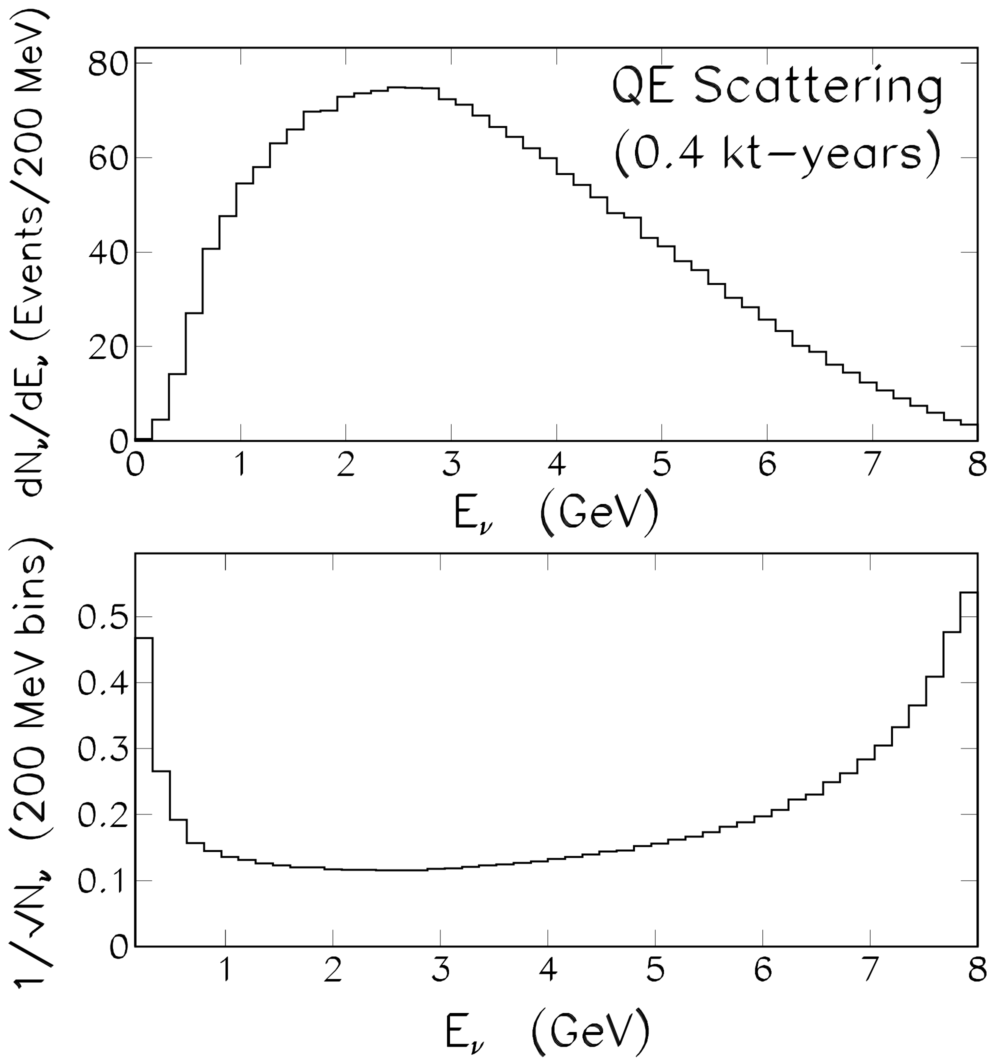

Figure 2: The predicted QE spectrum $dN_{\bar{\nu}_e}/dE_{\bar{\nu}_e}$ (top panel). The normalization corresponds to 4 years of data taking at the Debuncher with a 0.1 kt detector. The statistical precision corresponding to the predicted number of events in each 200 MeV bin is shown as a function of $E_{\bar{\nu}_e}$ in the bottom panel.

and

$$d\sigma(\nu_\mu n \to \mu^- p)/dE_\nu \;=\; 1\times10^{-38}\ \mathrm{cm}^2\ \text{ for }\ \mathrm{E}_\nu > 0.7\ \mathrm{GeV} \tag{2}$$

In our scenario we are interested in $\sigma(\bar{\nu}_e p \to e^+ n)$ rather than $\sigma(\nu_\mu n \to \mu^- p)$. Based on V-A fits to the QE data (Fig. 1) we will assume the antineutrino QE cross-section is two-thirds of the neutrino QE cross-section. The predicted spectrum $dN_{\bar{\nu}_e}/dE_{\bar{\nu}_e}$ is shown in the top panel of Fig. 2, where the normalization corresponds to 4 years of data taking at the Debuncher with a 0.1 kt detector. The predicted total QE event sample is 2100 events. The statistical precision corresponding to the predicted number of events in each 200 MeV bin is shown as a function of $E_{\bar{\nu}_e}$ in the lower panel of Fig. 2. Note that in the simulated scenario the cross-section is determined with a statistical precision better than 15% for each 200 MeV energy interval within the range 1 GeV $< E_\nu <$ 4.5 GeV.

4 Muon Polarization

The muons are born in the Debuncher with polarization $P = +1$. As they orbit the Debuncher the muon spins precess with a period $T_P \sim 20$ turns. The muon lifetime in the ring $\gamma\tau_\mu \sim 117$ turns. Therefore, since $\gamma\tau_\mu >> T_P$, the time-averaged polarization of the muons decaying in the straight section is expected to be close to zero. However, for a given muon decay occurring at a known time, in general the muon polarization will be finite and known. The muon polarization is important because it controls the distributions of neutrino and antineutrino energies in the beam. The good news is that knowledge of the time-dependent polarization can be exploited to determine the dependence of the observed event distributions on the incoming neutrino and antineutrino spectra. The bad news is that any uncertainty on the time averaged polarization will introduce an uncertainty in the measured cross-sections.

To gain insight into the uncertainty on the neutrino and antineutrino event rates that might arise due to an imprecise knowledge of the time averaged muon polarization in the ring, the predicted QE spectrum resulting from unpolarized muons ($P = 0$) is compared in the top panel of Fig. 3 with the corresponding spectrum resulting from muons with a polarization $P = 0.05$. The two spectra are very similar. The bin-by-bin ratios between the $P = 0$ and $P = 0.05$ predictions $\Delta R/R \equiv [N(P = 0.05) - N(P = 0)]/N(P = 0)$ are shown in the lower panel of Fig. 3. When P is changed from 0 to 0.05 the bin-by-bin shifts in the observed spectrum are at most $\pm4\%$, much smaller than the expected statistical uncertainty on the measurements. Hence, uncertainties on the muon polarization are probably not the limiting factor in the precision of the measurements.

5 Summary

The Debuncher provides us with a unique resource for:

(i) Measuring electron antineutrino cross-sections that are of importance, or will become important, for neutrino oscillation measurements.

(ii) Investigating the performance of candidate detector technologies that might be proposed for the next big step in the neutrino oscillation physics program at Superbeams and/or

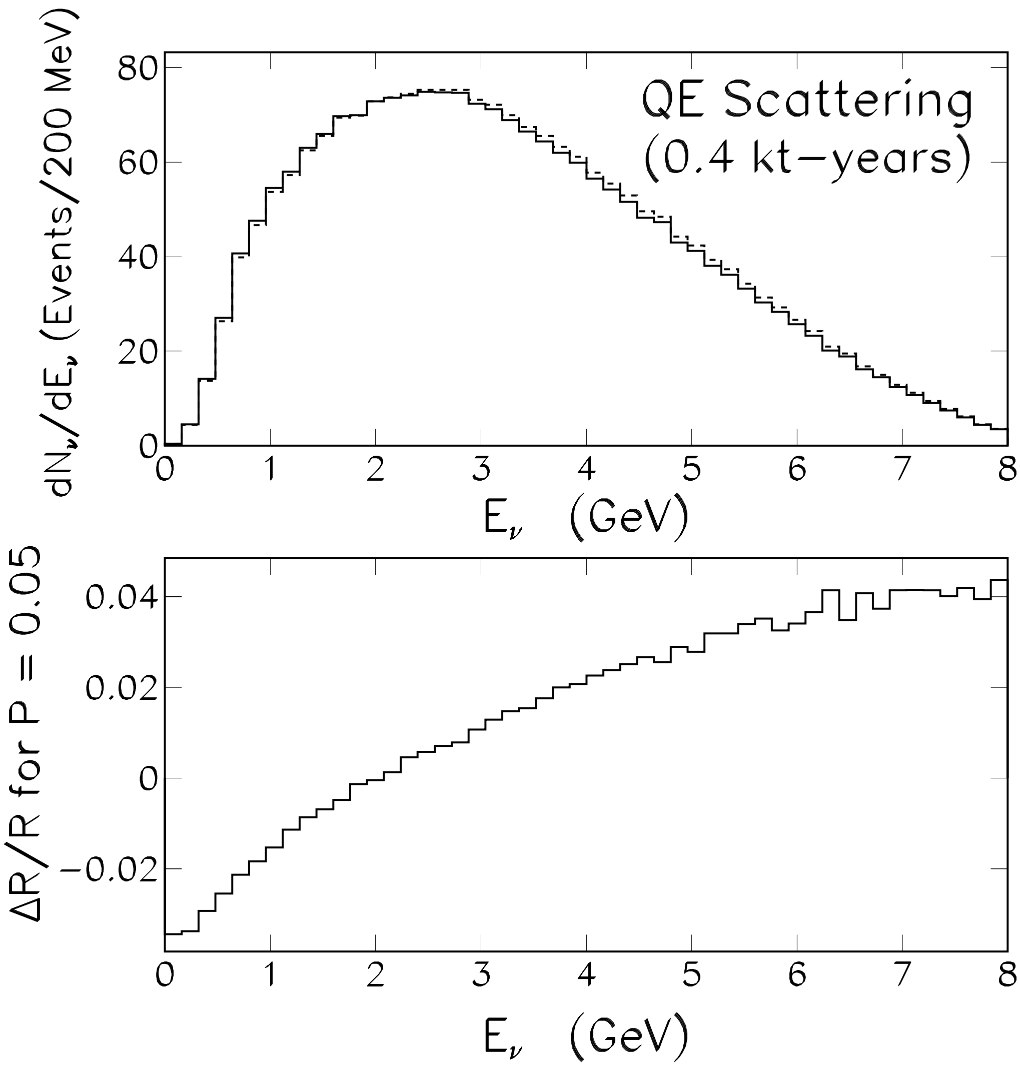

Figure 3: Predicted QE spectra resulting from unpolarized muons ($P = 0$) compared with the corresponding spectra resulting from muons with a polarization $P = 0.05$. The top panel shows the $P = 0$ (solid histogram) and $P = 0.05$ (broken histogram) spectra normalized to correspond to 4 years of data taking with a 0.1 kt detector. The bottom panel shows the bin-by-bin ratio $\Delta R/R = [N(P = 0.05) - N(P = 0)]/N(P = 0)$.

Neutrino Factories.

(iii) Studying backgrounds of importance to long baseline ν_e appearance searches.

The purpose of this note is to provoke some discussion that might lead to a proposal to develop a test area at the Debuncher, together with an associated detector R&D program plus an experiment to measure cross-sections. There are many open questions not addressed in this note, including whether the statistical precision is really sufficient for the desired cross-section measurements, whether the measurements will be spoiled by systematic uncertainties on, for example, the number of muon decays in the ring, whether it would be better to make ν_e cross-section measurements with a detector placed in the MINOS beam which would yield higher statistics (for ν_e not $\bar{\nu}_e$) but perhaps larger systematic uncertainties, and whether there are other potential uses for a Debuncher facility (for example, the facility might provide a $\bar{\nu}_e$ calibration source for MiniBooNE [10]). Finally, in the P-860 proposal the proposed mode of Debuncher running was in a reversed polarity mode optimized for ν_e measurements. It was shown that an order of magnitude increase in event rate might be obtained with optimized running. Dedicated reversed polarity running is presumably not viable until after the collider program is complete. However, in the post-collider period there may be an opportunity for a higher statistics experiment with dedicated Debuncher running.

Acknowledegments

This note was motivated in large part by a presentation at NUFACT01 in which it was proposed to build a low energy muon storage ring at the proposed CERN SPL, and measure the interesting neutrino cross-sections (M. Campanelli, S. Nevas, A. Rubbia [6]). A rapid understanding of the event rates at the Debuncher was made possible by the work done for the P-860 proposal [2, 9].

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